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LOW-PROFILE ANTENNA PERFORMANCE STUDY

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ECOM

US ARMY ELECTRONICS COMMAND FORT MONMOUTH, NEW JERSEY 07703

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The bandwidth and efficiency of antennas whose dimensions do not exceed one-tenth of a wavelength are discussed. A brief review of the Army's present VHF antenna capability is given. The distinction between "small" and "low-profile" is made and some basic principles relating to the efficiency and bandwidth of stub and loop antennas are studied. Top-loading and loading elements in the antenna structure (well-known techniques that have been used over the years) are most effective for improving the efficiency and bandwidth of small antennas. It was found that the configuration of the tuning and matching network plays an

20. Abstract (Cont'd)

important role in determining the instantaneous bandwidth of a system. In particular, it is shown that the parallel-input, two-element L-network provides wider bandwidth than does the series input L-network. In addition, it was found that the first element in the L-network, i.e., that nearest the antenna, is the primary source of constraints on the achievable instantaneous bandwidth.

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I. INTRODUCTION

An antenna is usually an easily-identified device, which if spotted by an enemy not only can compromise a position, but also can indicate the type of communication post in operation. For Army tactical radio communication systems, there has been, and remains, a critical requirement for low-silhouette, high-efficiency antennas with dimensions significantly smaller than a quarter-wavelength at the operating frequency. Recently, another requirement has been added for some applications: broadband operation, either on an instantaneous basis or by means of electronic tuning.

The major communication channel utilized by the Army is the VHF band from 30 to 76 MHz. There are only a few standard antennas being utilized, none of which combine all the necessary electrical and physical characteristics mentioned above. In fact, with the exception of one 3' whip, none of the antennas presently used is small compared to a quarter-wavelength.

This three-part series on electrically-small passive antennas provides a review of the literature and a summary of the current state-of-the-art. In addition, several recent designs and techniques which may improve the performance of small antennas will be examined. (Active antennas which incorporate active devices as part of the radiating structure may be a solution to the problems to be discussed. Good reviews of recent active antenna techniques are available [1], [2]. A selected bibliography is also included in Part III of the present series.)

This report, Part I, deals with a review of some well-established, basic methods to improve the efficiency of small-sized antennas as well as a discussion on bandwidth limitations. Part II will contain a survey of published broadband techniques for antennas; also included will be some numerical modeling results for several small antenna configurations; experimental results for a folded, loaded antenna will also be presented, and there will be a discussion concerning a recently-disclosed low-profile, broadband antenna [3]. Part III will be a selected bibliography on small antennas, from which it is hoped other researchers on small antennas will derive benefit.

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[1] Proceedings of the ECOM-ARO Workshop on Electrically Small Antennas, Editors: G. Goubau and F. Schwering (May 6-7, 1976, Fort Monmouth, NJ), October 1976, 240 pp. (AD A031845).

[2] Proceedings of the AP-S International Symposium, 1976 (Oct 11-15,1976, Amherst, MA), 613 pp. (IEEE Catalog No. 76CH1121-3AP; Library of Congress Catalog No. 66-9399.

[3] G. Goubau, "Multi-element monopole antennas," Proc. of ECOM-ARO Workshop on Electrically Small Antennas (Fort Monmouth, NJ, 6-7 May 1976), Editors: G. Goubau and F. Schwering, October 1976, pp. 63-67 (AD A03-1845).

In these reports, we will restrict our discussion to the 30-76 MHz band, since this band is of primary importance to the Army. It should be made clear, however, that in principle, our discussion is applicable to other frequencies; although at the higher frequencies, antennas are physically smaller at resonance. We wish to examine not only high-efficiency antennas, but also broadband antennas of small size and low profile. (We consider antennas to be small or of low profile when their maximum dimension is one-tenth of a wavelength or less.)

2. DISCUSSION

A. Present Army VHF Antennas

At the present time, the Army uses four standard VHF antennas: (1) The AS-1729: a 10' high, center-fed dipole antenna, which covers the 30 to 76 MHz range in 10 switched bands. It is a very efficient, vertically-polarized radiator and is used on jeeps, trucks, tanks, armored carriers, and shelters. (A 6' version, the AS-2731, is scheduled as its replacement; (2) The RC-292: a standard, fixed installation VHF antenna, which is a broadband 10' modified ground plane antenna. By changing the length of the four whip elements of this antenna, the entire VHF range can be covered; three such changes are necessary. (To eliminate element changing, a modification procedure to make the RC-292 a biconical antenna, is being distributed to users in the field. The OE-254, also a biconical antenna, has been type-classified and will eventually replace the RC-292 and any modified RC-292's in the field.); (3) The AT-271A/PRC: a 9' collapsible manpack antenna. This antenna is untuned and not very efficient below about 50 MHz; (4) The AT-892/PRC: also a manpack whip. At 3' in length, it is the only antenna which is small compared to a quarter-wavelength. It is untuned and very inefficient, except at the high-frequency end of the band. (Both of these untuned manpack whip antennas are strongly affected by their surroundings.) A development program to replace the latter two antennas is in progress.

The AS-1729 is large and highly efficient; however, it has narrow instantaneous bandwidth, and thus requires a complicated switched tuning system. The RC-292 is large, inefficient, and clumsy to handle, but relatively broadband. Unfortunately, its replacements are also large and clumsy to handle, but they have much wider bandwidths, which alleviates some of the handling problems. The current manpack whips are extremely inefficient narrow-band antennas, that must be excited against the small metal case of the present manpack radio. These antennas, as mentioned above, are extremely susceptible to changes in their surroundings. These difficulties are not expected to be markedly improved in future sets, since the overall size of the system will remain small compared to a wavelength.

The visibility and vulnerability of the antennas just discussed become critical problems when mounted on vehicles, especially armored vehicles. Most Army vehicles are of the order of one to three wavelengths in size, and therefore should provide good electrical support for antennas, especially small antennas operating at 30-76 MHz range. It is in the area of vehicular antennas that some good progress can be expected, not only from new antenna configurations, but possibly also from the exploration of techniques for intentional excitation of vehicles.

B. Small Antennas

(1) Review of desired electrical and mechanical characteristics. For Army applications, the bandwidth to be covered is 30-80 MHz, i.e., a little less than a 3:1 range. It is desirable that this frequency range be covered without tuning, or if bandswitching must be used, in two or three switched bands. Of course, a continuously tuned antenna still is, and will be, needed in some situations (e.g., changing environments where the antenna must be retuned to adapt to its surroundings). Devices for such applications are either already available or are being investigated at the present time. However, a broadband antenna of simple and reliable design is still needed for most Army applications.

A broadband antenna must also be an efficient radiator, since the Army communicates in the VHF band with limited RF power ($\lesssim$40 watts) and must cover, in some cases, a 10-to 15-mile range. In the past, broadband antennas have appeared, but in many, efficiency and, therefore, range have been traded off.

The most important characteristic which limits both the bandwidth and efficiency is size. By all currently-known theories, a small antenna (dimensions $\lesssim 0.1\lambda$) is a narrow-band, low-efficiency radiator. However, in the design of Army antennas, the term, "small antenna" has very often been a misnomer for "reduced height antenna." In other words, if the true constraint is on height rather than on overall size, it may be possible to achieve efficient broadband radiators of "low profile" or "reduced height" at the expense of increased volume. A very recent antenna design exploits this approach [3].

Most VHF antennas presently used by the Army have vertically polarized, omnidirectional radiation patterns in the azimuthal plane. A small vertical radiator also has such characteristics. However, for the VHF band, the mounting platform may be very important to the electrical performance of such a small antenna. Platform size may be comparable to a wavelength and thus cause significant distortion in the radiation pattern. Therefore, a knowledge of platform effects is also important in the design of small antennas. There are some cases in which a directive pattern may be desirable, or perhaps even necessary. In other cases, it may also be necessary to "steer" the pattern into a desired direction. In all cases where directivity is needed, several radiating elements and the associated phase shift and amplitude control circuitry are necessary. In this report, such complexities will not be considered.

There are several other characteristics, which although of lesser importance, should also be mentioned: survivability, mounting ease, mechanical simplicity, weight, and cost.

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[3] G. Goubau. (See Footnote on p 2).

No VHF antenna presently used by the Army combines all the characteristics described above in a single unit. In fact, it is not a certainty that such an antenna can ever be achieved. The first three parameters--bandwidth, efficiency, and size--and ways to improve them, will be examined in the following sections of this report.

(2) Efficiency of resonant and non-resonant antennas. The efficiency of an antenna is strongly dependent on its resonant condition. Consider the $\lambda/4$ antenna of Fig. 1a. This is the common resonant monopole excited against

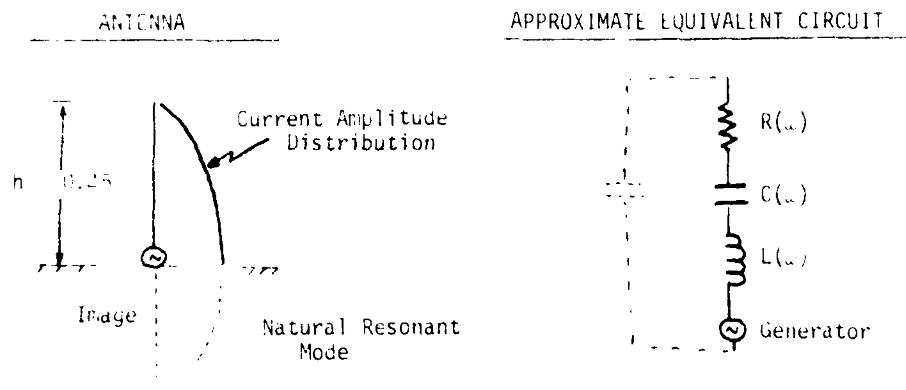

Fig. 1a. Resonant monopole antenna.

a ground plane. If this antenna is very thin, the current distribution is nearly sinusoidal and the structure has a natural resonance at approximately the length shown.

If we assume that the metal wire forming the whip has negligible losses, the only loss in the system will be the so-called radiation resistance. If the generator is matched to this resistance, $R(\omega_0)$, all of the available power will be radiated, and the efficiency will be 100%.

If we reduce the antenna length to 0.1λ, as in the case of Fig. 1b, the

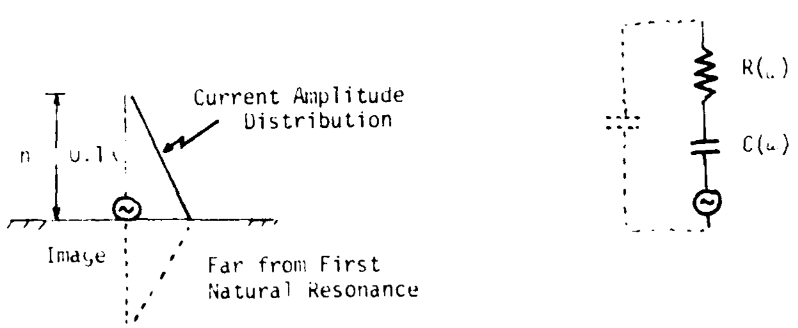

Fig. 1b. Non-resonant small antenna.

antenna will be far from a natural resonance; the current distribution will be almost linear; and its amplitude will be much lower than that for the case shown in Fig. 1a. The equivalent circuit then simplifies to a frequency-dependent resistance (radiation resistance) in series with a frequency-dependent capacitance of small value. The capacitive reactance will be much greater than the resistance; hence, much less power can be delivered from the generator. Again, all losses in the conductor are neglected. The overall efficiency in this case may be only a few percent.

The antenna of Fig 1b is not resonant. To induce resonance, an inductance may be added in series with the antenna and the generator. As shown in Fig. 1c, the location of this inductance (i.e., above the ground at some

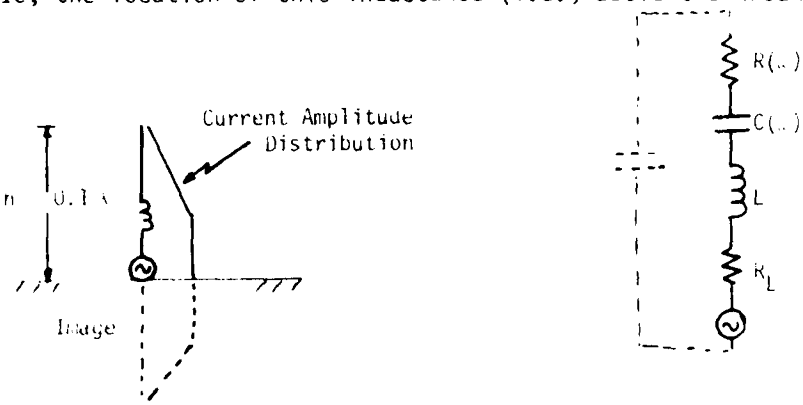

Fig. 1c. Resonated short antenna.

point in the antenna structure, or completely below the ground plane) affects the overall efficiency of the system In any case, this inductance does two things to the system: (1) A resonant circuit is achieved if L is chosen properly, and (2) A resistance which consumes power and dissipates it in the form of heat rather than in the form of RF radiation is added to the system. The location of L in the radiating structure affects the value of the radiation resistance $R(\omega)$ in the sense that the current distribution along the antenna is modified as shown in Fig. 1c. In fact, the distribution becomes approximately constant over a portion of the antenna. In the past, it was found empirically, and more recently verified by computer [4], that with regard to efficiency an optimum location for this inductance is about four-tenths of the length of the antenna above the ground plane.

In general, the inductance must be changed if the antenna is to resonate at a different frequency. (This is the basic tuning technique used when operating over a band of frequencies.) However, the radiation efficiency of this inductively-loaded antenna,

$$\eta = \frac{R(\omega)}{R(\omega) + R_L} \qquad (1)$$

[4] R.C. Hansen, "Efficiency & Matching Tradeoffs for Inductively Loaded Short Antennas, IEEE Trans. on Com., Vol. COM-23, #4, Apr 75, pp. 430-435.

is still small (in practice, of the order of 10% at the lower end of the band). The overall system efficiency will still be very low, because the generator and the antenna will usually be mismatched, i.e., the total available power will not be delivered to the load. In general, the R_L in the equivalent circuit of Fig. 1c represents all the losses present in the circuit, except the radiation loss.

Top loading (as shown in Figs. 2a and 2b) is another traditional approach

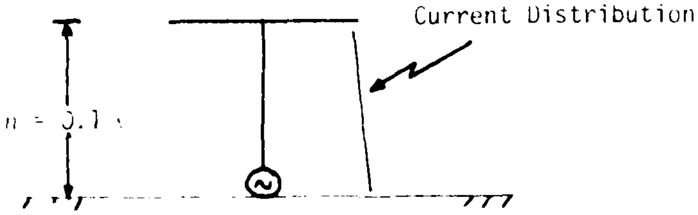

Fig. 2a. Top loaded short antenna.

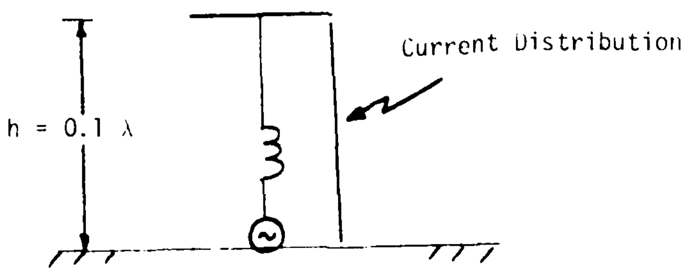

Fig. 2b. Top loaded-inductively loaded short antenna.

towards achieving a fairly high efficiency in a relatively-small-sized antenna. Note that the current distribution in these structures is almost constant. This feature, i.e, constant current distribution, and the resonance condition are seen to be key factors in achieving reasonable efficiency in a small antenna; the incorporation of network elements, i.e., capacitors and inductors, into the radiating structure is another technique that yields favorable results.

(3) The importance of tuning and matching networks for efficiency. It seems clear that it is not the radiating element that is inefficient, but the tuning and matching networks needed to resonate the antenna and match it to the generator that contribute directly to the inefficiency of small antennas. The antenna itself contributes only indirectly, by possessing an input impedance which usually necessitates the use of inductors and capacitors with values such that the limits of practical, low-loss circuit elements are exceeded. To illustrate this point, Tables I and II have been

TABLE I
Input Impedance and Efficiency of Very Short Copper Stub Over Infinite Ground Plane. Diameter of Stub is $3.3 \times 10^{-4}\lambda$.

Length of Stub (wavelengths)	Input Impedance	Efficiency (lossless network)	With Tuning Coil Q=100	Q=400
0.00159	0.0009-j9759	84.9%	9.7×10^{-6}%	3.9×10^{-5}%
0.00319	0.0033-j6546	91.2	4.9×10^{-5}	1.9×10^{-4}
0.00478	0.0097-j4757	93.9	2.0×15^{-4}	8.1×10^{-4}
0.00637	0.0151-j3901	95.7	3.8×10^{-4}	1.5×10^{-3}
0.00796	0.0241-j3365	96.5	7.1×10^{-4}	2.9×10^{-3}
0.00955	0.0351-j2971	97.1	1.2×10^{-3}	4.7×10^{-3}
0.01114	0.0482-j2669	97.5	1.8×10^{-3}	7.2×10^{-3}
0.01273	0.0634-j2429	97.8	2.6×10^{-7}	10.4×10^{-3}
0.01433	0.0807-j2235	98.9	0.004	0.014
0.01592	0.1000-j2071	98.2	0.005	0.019

TABLE II
Input Impedance and Efficiency of Small Copper Loop with One Turn. Diameter of wire is $3.3\times10^{-4}\lambda$.

Circumference of Loop (Wavelengths)	Input Impedance of Loop	Lossless Tuner	Efficiency Tuning Cap Q=1000	Tuning Cap Q=4000
0.01	0.0035+j 4.50	0.06%	0.02%	0.03%
0.02	0.0071+j22.75	0.4	0.11	0.25
0.03	0.0108+j38.25	1.5	0.33	0.79
0.04	0.0138+j55.23	3.5	0.74	1.81
0.05	0.192 +j73.75	6.6	1.37	3.38
0.06	0.0243+j92.33	10.9	2.27	5.59
0.07	0.0305+j112.36	16.4	3.50	8.53
0.08	0.0382+j133.19	22.7	5.06	12.13
0.09	0.0477+j154.77	29.6	6.91	16.20
0.10	0.0598+j177.28	36.8	9.28	21.13

extracted from a report by Ohio State University [5]. The conduction losses of the wires used for the radiating structures have been included in the calculations, which is why the efficiency in the lossless matching network columns is not 100%. Table 1 gives the efficiency of an extremely-short stub antenna tuned by using a high quality (Q = 400) or a low quality (Q = 100) inductance of proper value to resonate the stub. These Q values are achievable in practical coil designs. Corresponding data is given in Table II for a loop, whose diameter was roughly twice the height of the stub, but still extremely small. The loop was tuned by using capacitors with Q's of [illegible] and 4000. In general, it is easier to construct low-loss capacitors than it is to construct low-loss inductors.

It can be seen from these tables that there was a dramatic difference in efficiency as a result of changing from low-Q to high-Q elements. The greater efficiency of the loop over that of the stub was even more dramatic, although the conduction losses of the loop were greater than those of the stub (as evidenced by a comparison of the efficiencies using lossless tuners).

The data tends to indicate that: (1) for low losses, an all-capacitator tuning network is desirable, and (2) since the loop has the proper input impedance to use capacitive elements effectively, the loop will always be more efficient, granting its larger size and the need for tuning networks.

There are, however, other characteristics of the loop (to be discussed in succeeding sections) which may make it less attractive. Also not considered in these tables is the transformation which is necessary to bring the value of the real part of each antenna (at resonance) to that of the input impedance of the generator, resulting in the transfer of maximum available power. It will be seen, however, that at a specific frequency, a rather simple network can be used to accomplish transformation.

(4) The bandwidth of small antennas.

(a) Overview: During the ECOM-ARO Workshop on Small Antennas, [1], two fundamental questions were raised: Is there a basic limitation on the bandwidth of an antenna as a function of its size? And, if such a limitation exists, what is the underlying principle?

In the previous section, we saw that the efficiency of a small antenna can be increased by using certain loading techniques. In general, utilization of these techniques increases the instantaneous bandwidth over which efficient operation is achievable, because the difference between the electric and magnetic stored energy is decreased.

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[5] C.H. Walter, E.H. Newman, Ohio State University Electroscience Lab, USAMC Contract #DAAG-39-72-C-0041, Rpt. #HDL-TR-041-1, Feb 1974.

[1] Proceedings, ECOM-ARO Workshop on Electrically Small Antennas (see p.2).

A. Alford [6], has provided an elegant description of an antenna used as a transformer for converting guided electromagnetic waves into free-space waves. If this transformation is accomplished on a gradual basis, e.g., via an exponentially tapered structure (see Fig. 3) a broadband response is achieved, viewed in terms of maintaining a specified input impedance range. If, however, there are abrupt variations in the dimensions of the structure, energy is reflected back toward the source. This reflection and any other reflection points in the transmission path given rise to unwanted resonances and make the structure frequency-sensitive. Alford points out, however, that the structure of his antenna (Fig. 3) can be "distorted" into many shapes while still maintaining a reasonably gradual taper. He notes that for minimum reflections, the final opening or aperture should be of the order of a wavelength. In the case of small antennas, such as those being considered in this report, the change from transmission line to free space is usually very abrupt. Large reflections occur, and so the bandwidth is extremely narrow. The question then arises: Is it possible within the constraints of a maximum dimension of 0.1λ to build an antenna with broad bandwidth?

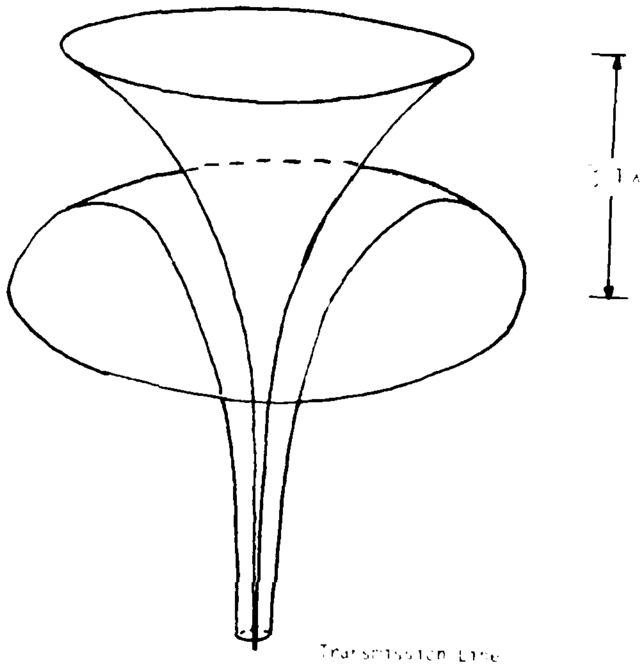

Fig. 3.
Broadband antenna structure
(according to A. Alford [6]).

In the discussion of the efficiency of small antennas, it was seen that the Q of the tuning elements exerted a great influence on the efficiency. The Q is also a measure of the bandwidth of a network and is defined, for high Q values, in approximation, as

$$Q \simeq f_0/\Delta f \ , \qquad (2)$$

where f_0 is the resonant frequency of the circuit and f is the difference between two frequencies in the vicinity of f_0; here half the power being delivered to the circuit is reflected. However, with this definition of Q,

[6] A. Alford, Very High Frequency Techniques, New York: McGraw-Hill 1947, Chapter 1.

the resulting VSWR at the band edges exceeds 5:1. For Army equipment, a VSWR $\leq$3:1 is usually considered acceptable; thus, the bandwidth determined from Eq. (2), under the 3:1 VSWR constraint, is even smaller than and the Q value greater than that based on the half power constraint.

A second definition of Q is usually made in terms of the impedance parameters, i.e.,

$$Q = \frac{|X|}{R} \tag{3}$$

where $|X|$, is the reactance of a circuit and a measure of the stored energy, and R represents the losses or dissipated power. The reactance $|X|$ is, really, the difference between peak-electric and magnetic-stored energy. In the small antennas considered in Fig. 1, the stored energy is almost entirely electric because of the large capacitive reactance. Thus the value of Q from Eq. (3) is very large, especially since the radiation resistance, R, of the small antennas considered, is much less than 1. As seen from Eq. (2), the resulting bandwidtn is extremely narrow. However, $|X|$ represents the difference between the electric and magnetic energy stored in a system, and has been pointed out elsewhere [7], it may be entirely possible to maintain extremely-high electric and magnetic stored energy in a system, while their difference remains small. Consequently, in the sense of Eqs. (2) and (3), it may be possible to have a large bandwidth even in a small antenna where the energy storage is usually high, insofar as an antenna's input impedance variation can be represented over a band of frequencies by an equivalent circuit, Eq. (3) is meaningful. However, it will be shown that when used to determine the bandwidth of an antenna, Eq. (2) is a very poor approximation.

(b) The Bandwidth of Stub- and Loop Antennas: It was mentioned earlier that for a given frequency there is a simple network which can provide the transformation necessary for a perfect match between an antenna and the generator. This network is called an L-network. Typical L-network configurations for matching electric and magnetic dipoles to a source or load are shown in Fig. 4. In order to estimate the bandwidth of an antenna, we consider the following problem encountered in matching the stub or loop when an L-network is used. If we know the input impedance variation of the stub or loop antenna, the required impedance variation for the two elements of the L-network can be calculated to achieve the desired match conditions. The input VSWR after matching is allowed to be as great as 3:1. Then the network element impedance variations are compared to those of realizable, passive capacitor-and inductor elements. By this comparison procedure, we can determine the achievable bandwidth of an antenna in combination with an L-network consisting of lossless elements. The bandwidth thus determined can be compared with the bandwidth values found by using Eqs. (2) and (3) and the antenna input impedance.

The operation of tuning and matching the L-network is described in Appendix 1, along with the derivation of the equations needed to determine the quantities described in the above problem.

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[7] Editors' Comments, Proc of the ECOM-ARO Workshop on Electrically Small Antennas, Ed: G. Goubau and F. Schwering (Fort Monmouth, NJ, 6-7 May 1976) October 1976, pp. 228-229 (AD 031845).

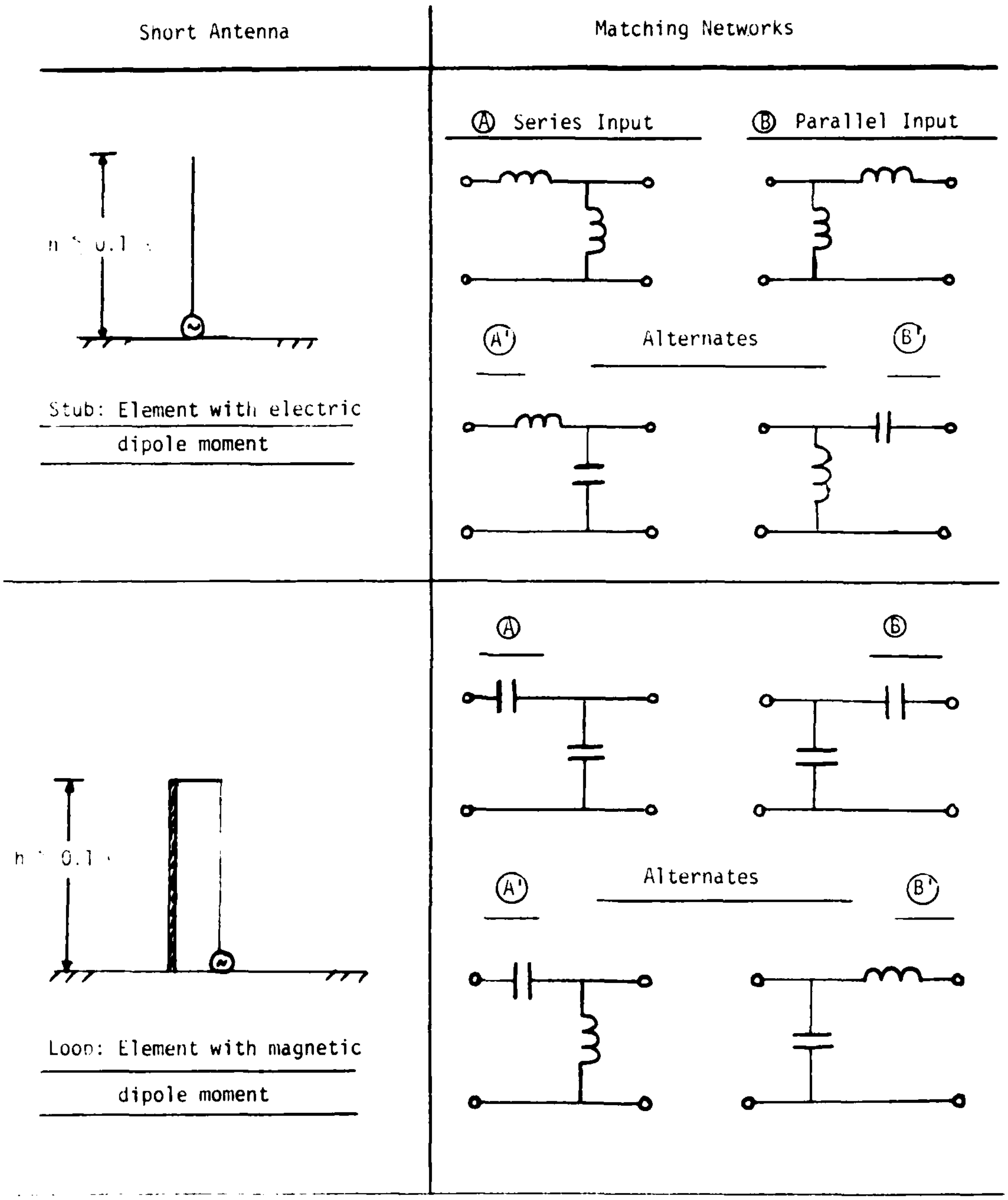

Fig. 4.
L-networks used for matching stub and loop antennas.

A moment-method solution [8] of the input impedance of stub- and loop antennas provides accurate results upon which to base the bandwidth calculations. (Experimentally accurate results are not easily attainable, due to the extremely small resistance values in combination with large reactance values for the small antennas being considered). The resistance and reactance variation of the stub and the loop are shown in Fig. 5.

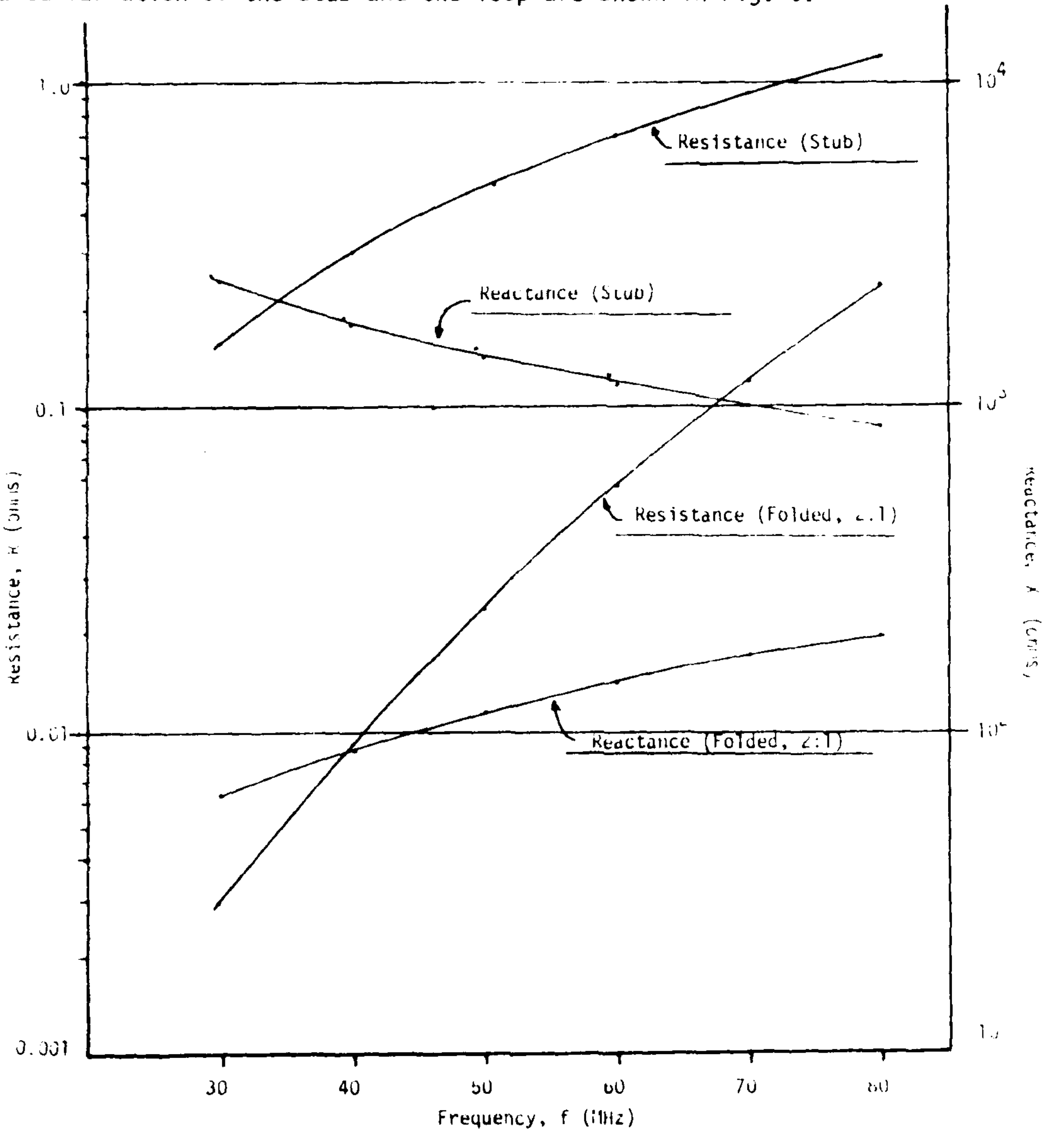

Fig. 5
Calculated input impedance of 0.1λ high stub and loop.

[8] MBA Computer Program

In Figures 6 and 7, the impedance variations required to match a stub antenna to a VSWR ≤3:1 by using a series input, inductive L-network are shown (Network type (A) of Fig. 4). The required series element variation is shown in Fig. 6. The curves R=3, R=1, and R=0.33 represent impedance variations where the real part of the antenna impedance transformed by the series element of the L-network is three times, equal to, and one-third respectively, that of the desired impedance. The high- and low-value curves represent the 3:1 VSWR limits. The Series L curve gives the impedance variation of a realizable, passive series, inductive reactance. Note that since the inductance is lossless, this variation, in addition to being realizable, is also ideal.

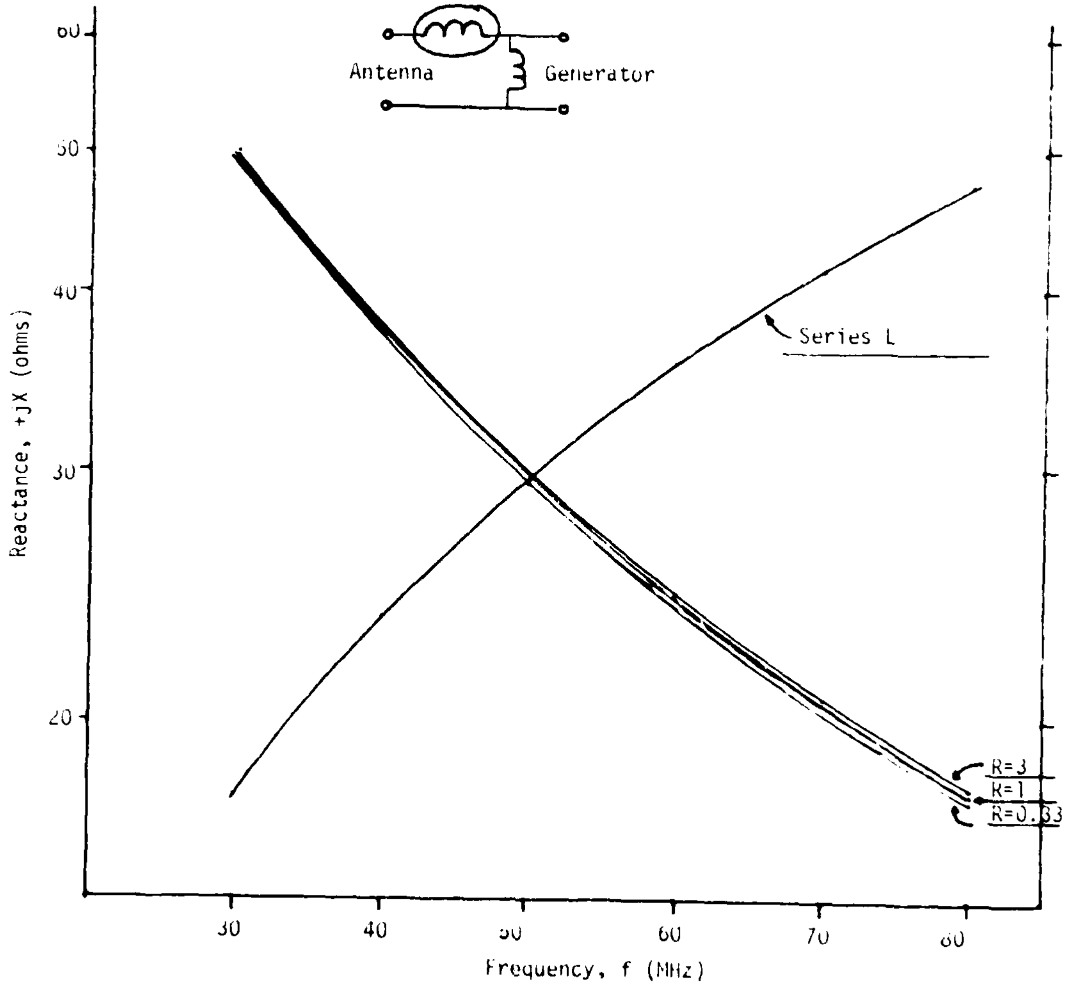

Fig. 6
Stub: series input L-network required and realizable first element variations.

The intersection of the Series L curve and the R curves is a measure of the instantaneous bandwidth of the combination of the antenna and the series tuning element. To determine if any further bandwidth restrictions exist, we must also examine the required impedance variations of the second element. This information is presented in Fig. 7, where the three R-value curves are again plotted; this time, however, they represent the variation of the parallel element of the L-network, required to maintain an input VSWR $\leq$3:1. The realizable, parallel inductive susceptance curve, Parallel L, is also shown. The remarkable feature of Fig. 7 is that over the entire frequency range the realizable Parallel L curve practically coincides with the R=1 curve. Thus, we see in this case, that the second- or parallel element imposes no significant bandwidth restrictions on the system.

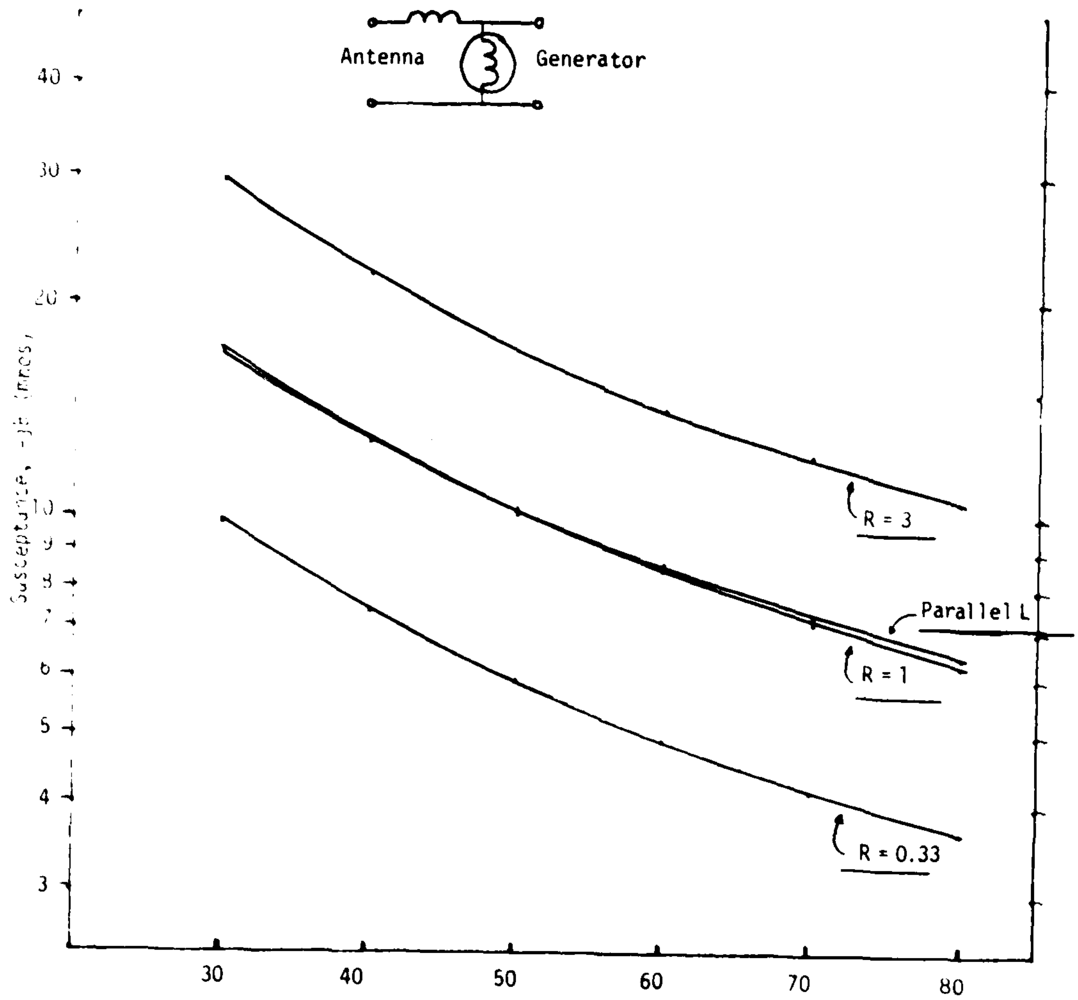

Fig. 7.
Stub: series input L-network required and realizable second element variations.

It is also possible to tune and match the stub antenna using a shunt-inductance-input version of the L-network (Network type (B) of Fig. 4). The required shunt and series impedance variations have been calculated and are shown in Fig. 8 and Fig 9, respectively. The 3:1 VSWR-limit curves are plotted together with the realizable shunt-and series element variations. These curves again show that the first element in the L-network (in this case a shunt inductance) limits the achievable instantaneous bandwidth, although the second element is not critical. Note in Fig. 9 that, in contrast to Fig. 7, the series element no longer tracks the required variation, and so does put a further limit on the bandwidth. This, however, is not a severe constraint.

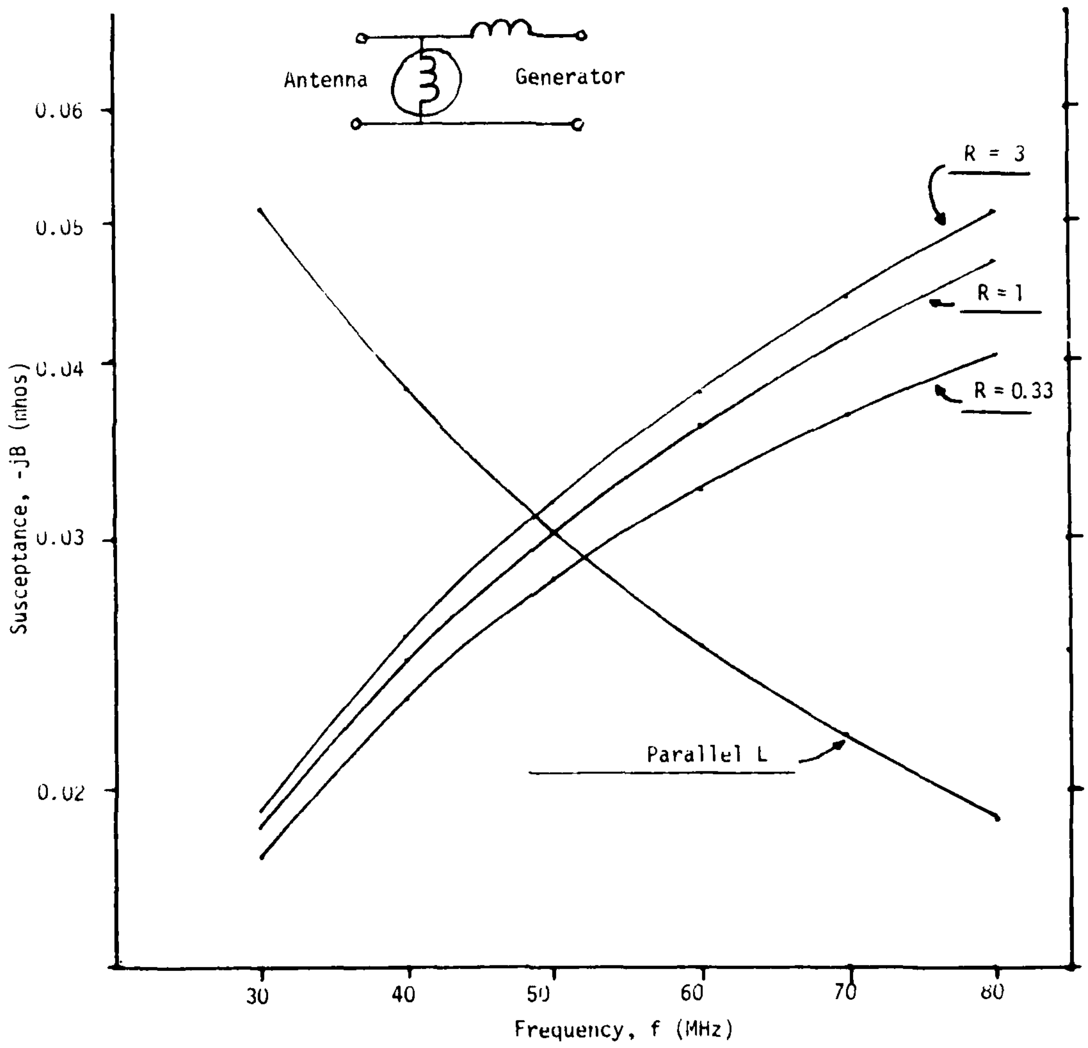

Fig. 8.
Stub: parallel input L-network required and realizable first element variations.

A more striking comparison is seen in the curves of Figs. 6 and 8. Although the first element in each case limits the bandwidth, the shunt element variation depicted in Fig. 8 permits a far wider bandwidth in realizable circuits than does the series element variation of Fig. 6.

Network types (A) and (B) in Fig. 4 can be changed to network types (A') and (B') by increasing the immitance of the input element of the L-network as described in the Appendix. For the series input L-network, there is no bandwidth advantage to be gained by changing the network; in fact, a bandwidth limitation of the type indicated in Fig. 9 is introduced by such a change. On the other hand, when tuning and matching the stub antenna a change from Network (B) to Network (B') is beneficial, since the realizable variation of the second element will now track the required immitance variation. However, as determined from the constraints imposed by the first element, there is a slight decrease in the bandwidth.

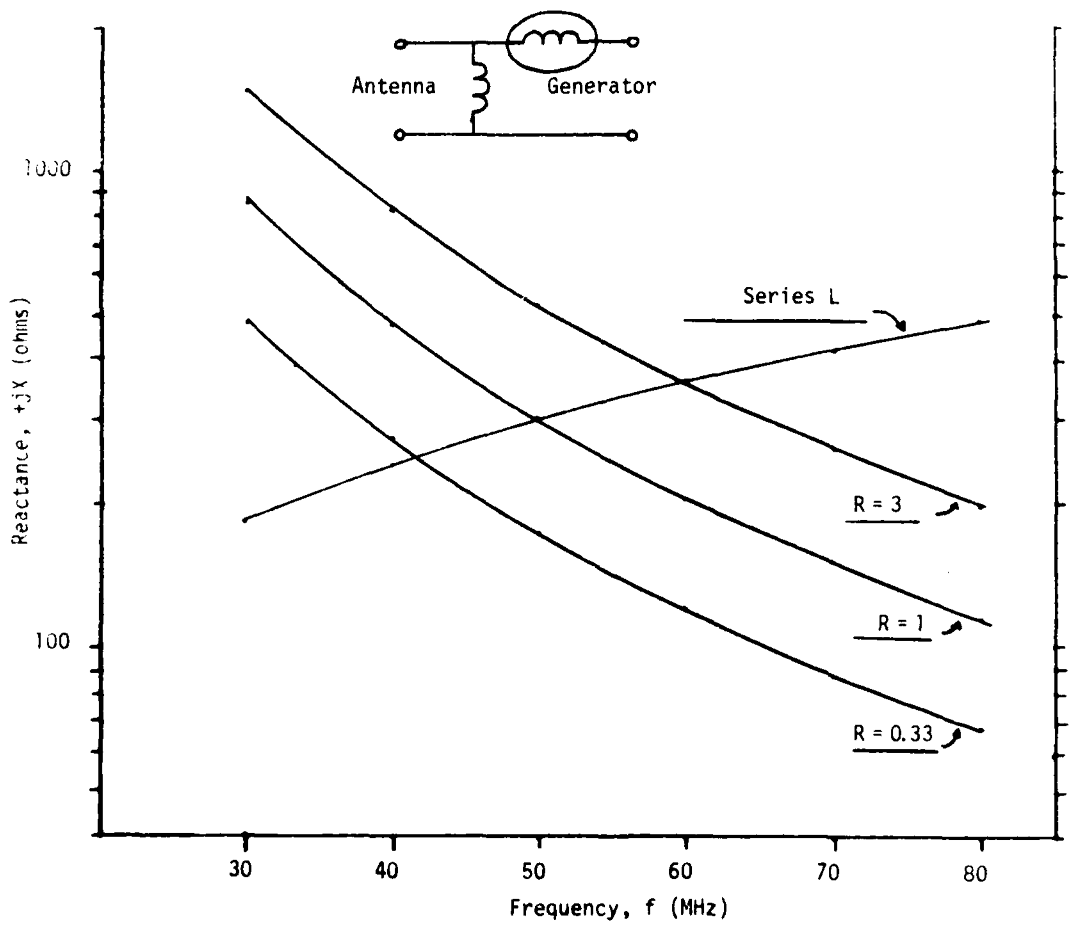

Fig. 9
Stub: parallel input L-network required and realizable second element variations.

A similar analysis of the L-networks required for tuning and matching a loop antenna was performed. The loop was assumed to have the same height as the stub just considered. However, the loop was modeled as a folded monopole above a ground plane; in addition, the radius of the grounded vertical element was assumed to be double that of the driven element. This tends to make the input resistance greater than the input resistance of the plain loop (no radius variations), which is extremely small for the small loop being considered.

The immitance variations required for the series input L-network, (type A of Fig. 4 for the loop or magnetic dipole element) are plotted in Figs. 10 and 11. As before, the variations required to maintain a 3:1 VSWR limit

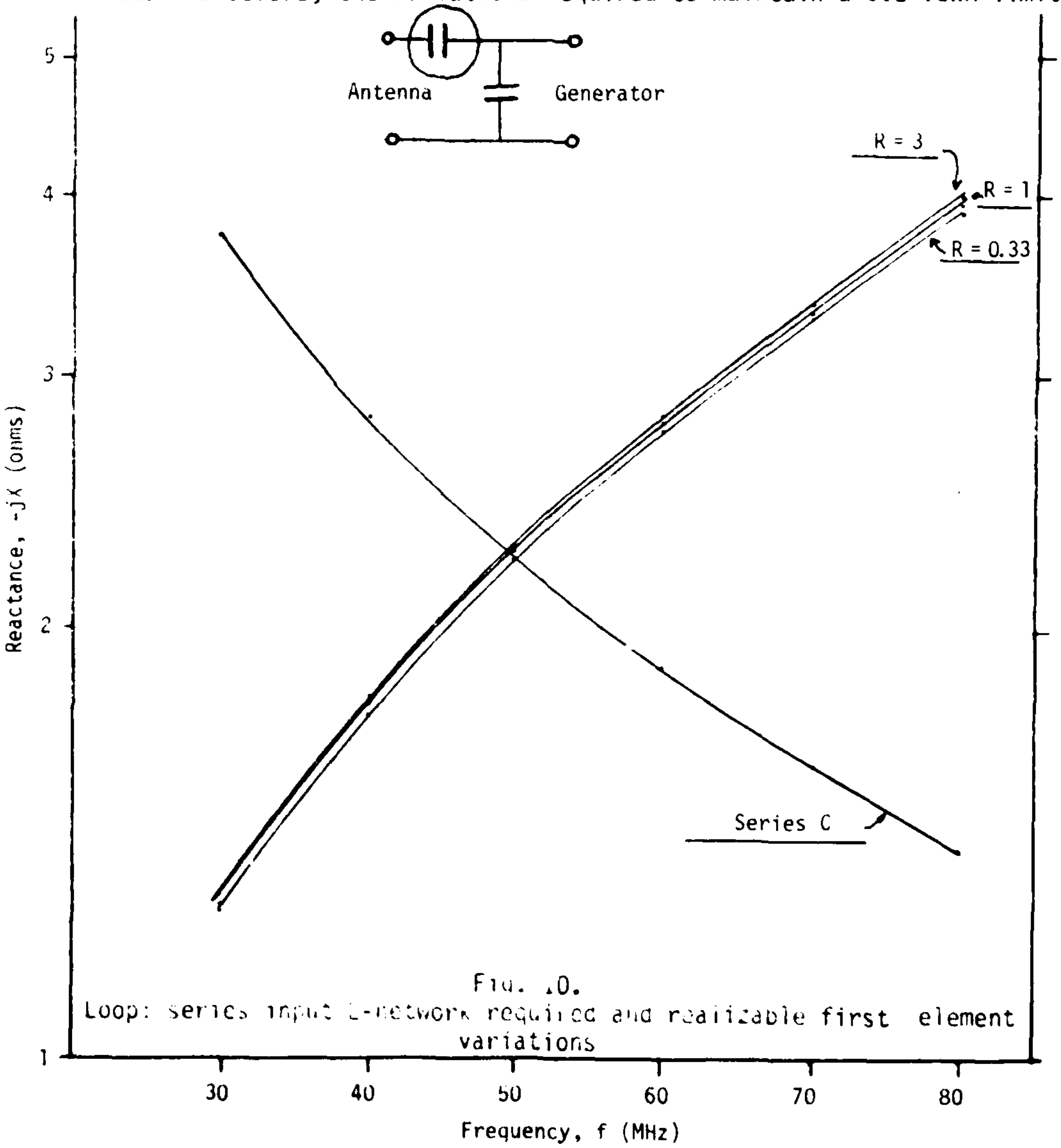

Fig. 10.
Loop: series input L-network required and realizable first element variations

are shown, as well as the realizable series- and shunt element variations. Note, again, that the first element--in this case the series capacitor-- limits the instantaneous bandwidth severely, but that the parallel element--also a capacitor--imposes a much less stringent limit on the achievable bandwidth. An increase in the immitance of the first element makes it possible to change the second element from a capacitance to an inductance, the immitance variation of which would track the desired variation. However, in practical cases, the inductance adds more loss to the system than the capacitor does, and so efficiency decreases. Thus, due to other considerations such as increased losses, the change may not be advisable.

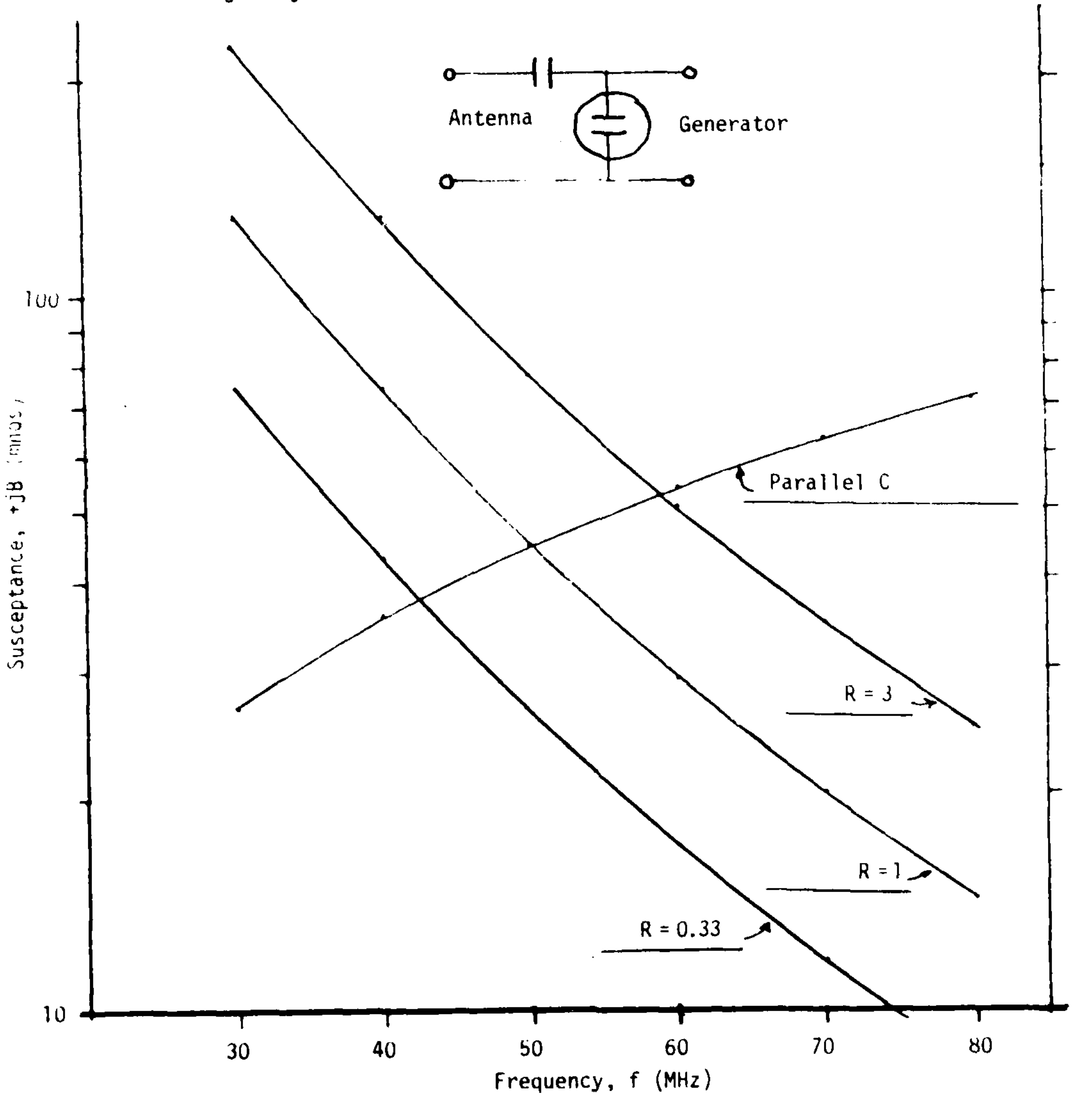

Fig. 11.
Loop: series input L-network required and realizable second element variations.

The variations of the parallel input L-network that were necessary to tune and match the loop are shown in Figs. 12 and 13. A comparison of the curves of Figs. 10 and 12 shows that the bandwidth limitations were eased somewhat in the latter case. In addition, the desired variation and realizable variation of the second element tracked fairly well. We see that, as for the case of the stub, the parallel-input L-network displayed more desirable bandwidth characteristics then the series input L-network. However, for the dimensions considered, the stub combined with the parallel-input L-network exhibited better bandwidth characteristics than did its loop, L-network counterpart.

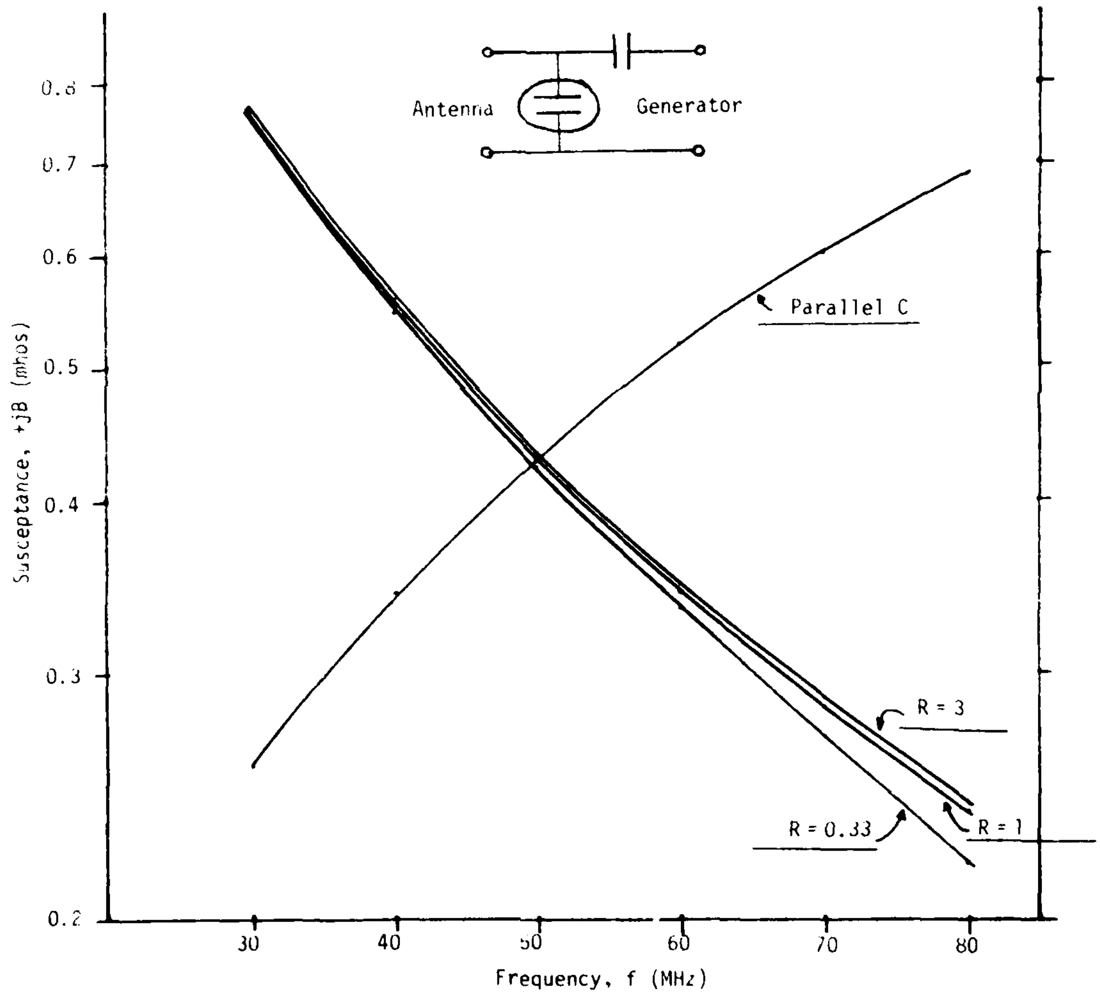

Fig. 12
Loop: parallel input L-network required and realizable first element variations.

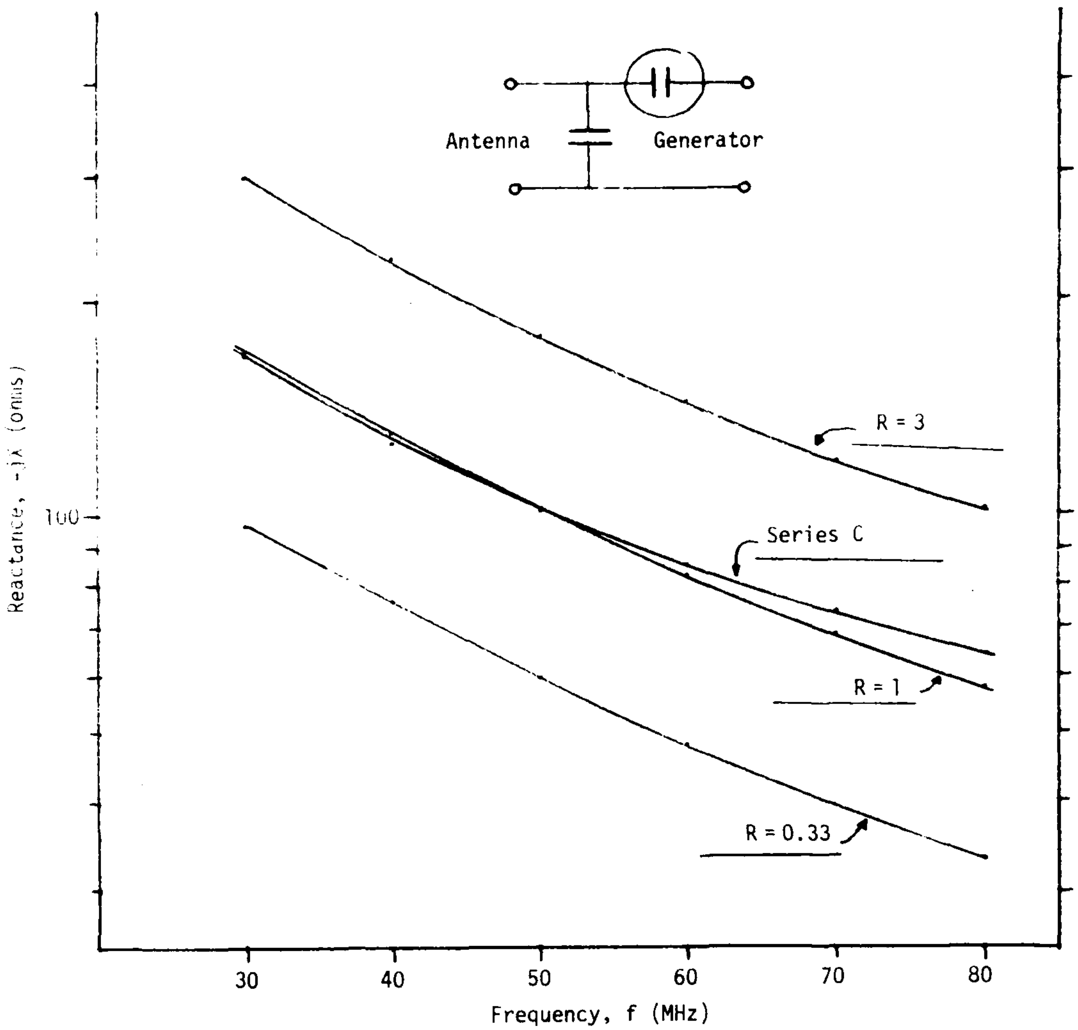

Fig. 13.
Loop: parallel input L-network required and realizable second element variations.

(c) Q Factor of Small Antennas: To complete this basic study we will compare the best-case bandwidth achieved for the stub, L-network combination with the bandwidth calculated using Eqs.(2) and (3). Figure 14 shows the

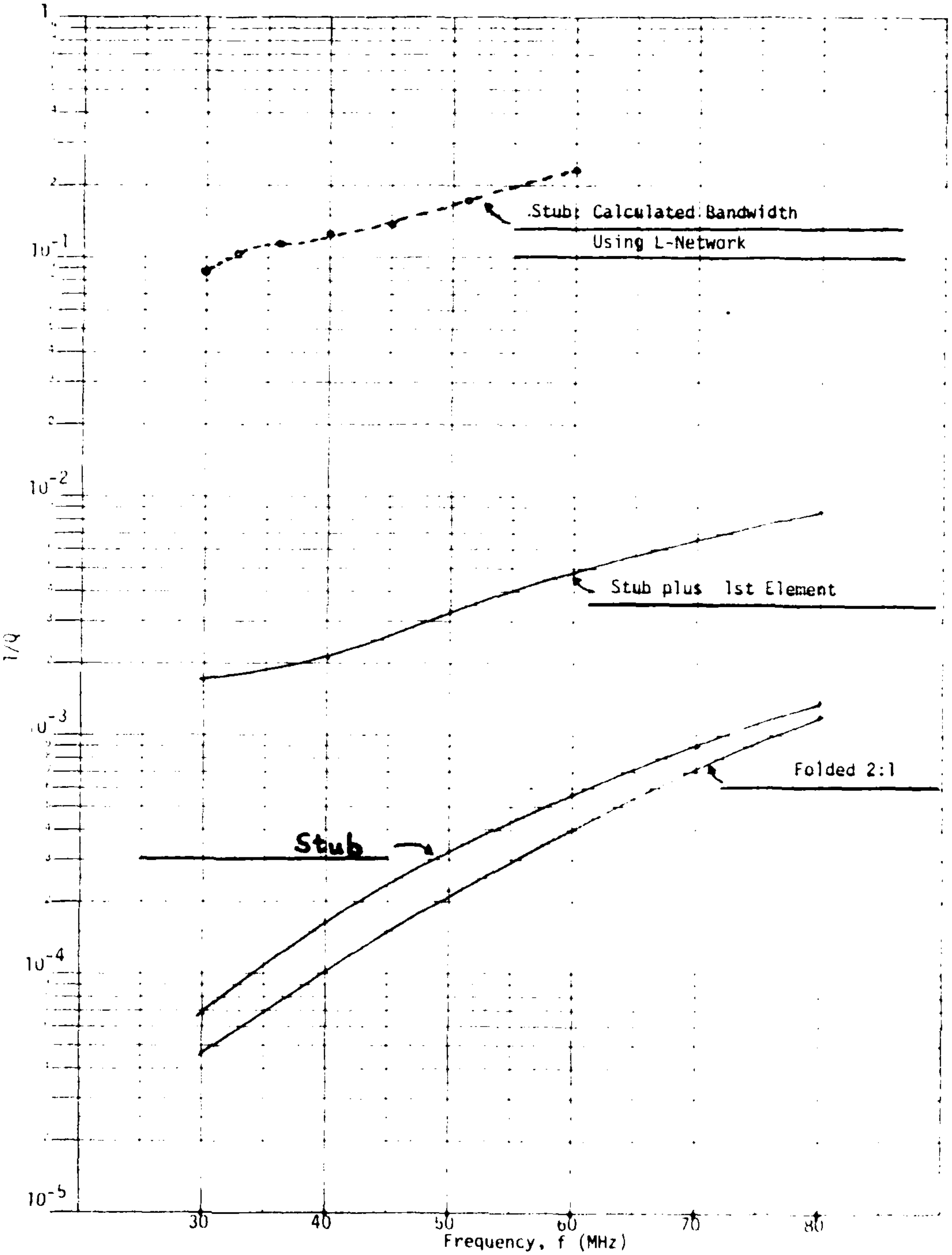

Fig. 14. Quality Factor of Small Antennas.

variation of the several small antenna types considered during this study, as well as a curve for the maximum possible bandwidth achievable with the stub, L-network combination. As before, the input impedance of each of these antenna types was calculated by computer using a moments-method approach. It can be seen that neither the slopes of the 1/Q curves nor their magnitudes are comparable with the curve illustrating the bandwidth of the stub-L-network system. Thus, the 1/Q variation is a very poor approximation upon which to estimate the bandwidth of an antenna. The maximum bandwidth was determined by noting from Fig. 8 (as from all the other figures) that: (1) a zero-slope immitance variation is the limit that can ever be achieved using passive lossless elements, i.e., elements obeying Foster's reactance theorem,*,and (2) that this zero-slope characteristic can be closely approached by replacing each of the indivudual elements with networks of elements.

3. CONCLUSIONS

We have seen that the efficiency of a small antenna is determined by the losses present in the tuning and matching networks used; and that resonance is a desirable condition for maximum overall efficiency. We have also stated that by loading the antenna--by top capacities, inductors, or combinations of both--the efficiency of a small antenna can be improved. These techniques are well documented in the literature.

With regard to bandwidth, we have examined very simple structures and their L-network tuning and matching systems, and have shown that even in such simple systems, the Q of the antenna does not constrain the bandwidth. We have also shown that for the case of the two element L-network there are differences in bandwidth resulting from the various possible configurations, and that the first element in such a network causes the dominant bandwidth constraints. To the author's knowledge, this fact has not been disclosed before in the literature.

4. RECOMMENDATIONS

Other antenna configurations, such as top-loaded monopoles and folded monopoles, are being investigated as a part of a follow-on program to determine the bandwidth constraints imposed by an L-network. The relationship between bandwidth and antenna size should be examined more carefully. Aspects of this problem will be discussed in Part II of this report series. In addition, a more complicated network--using three elements in the form of a "tee" or a "pi" should be examined to determine the bandwidth constraints.

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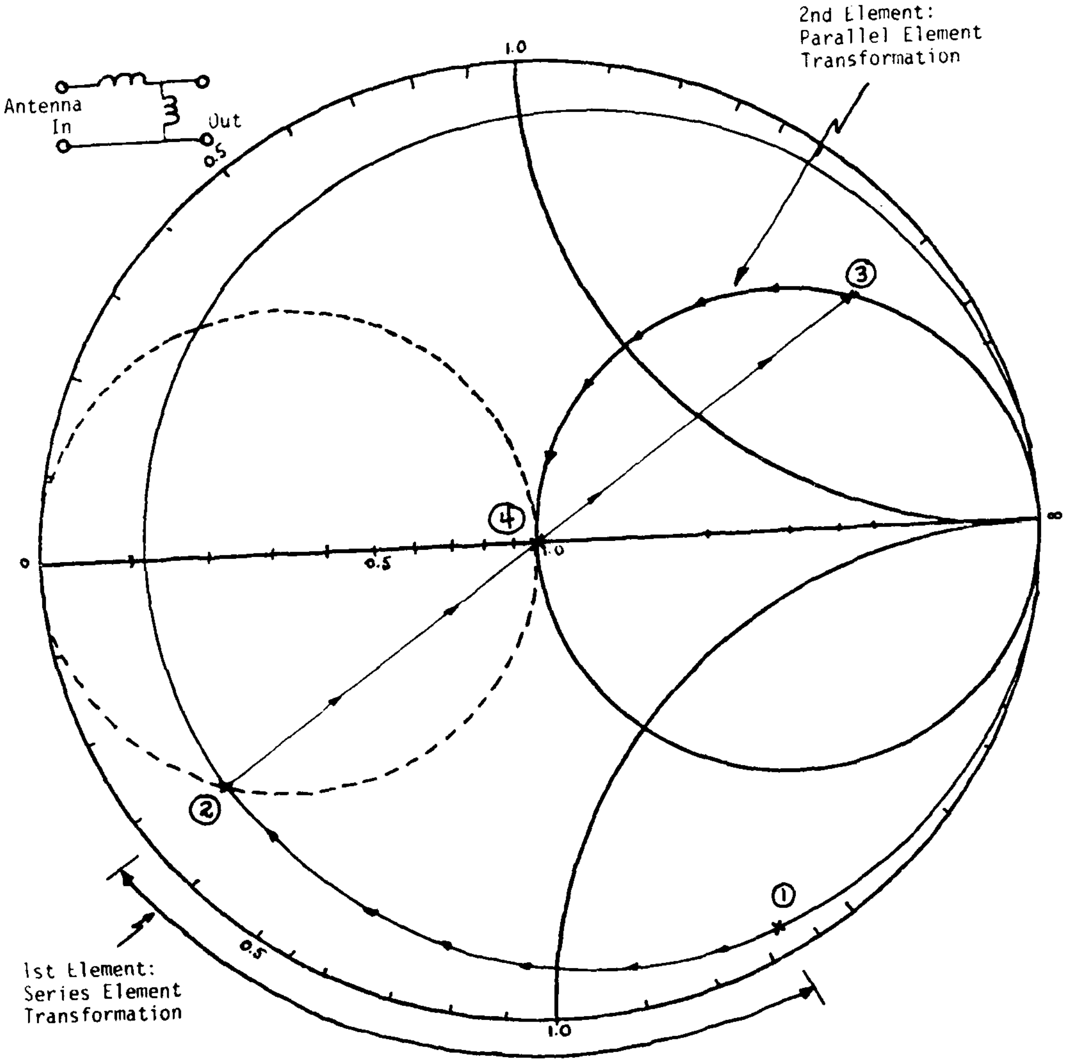
*Foster's reactance theorem in simplified form, states that the slopeof a reactance function as frequency is always positive, and must be greater than the slope of a straight line from the origin to any point on the curve of the function.

APPENDIX

Equations for Calculating the Required Immitance Variations of an L-Network Used to Tune and Match an Antenna to a Source or Load.

The two-element L-network provides the proper transformation to tune and match an antenna to a source or load at any given frequency. As an example of this tuning procedure, consider the Smith chart plot of Fig. A-1.

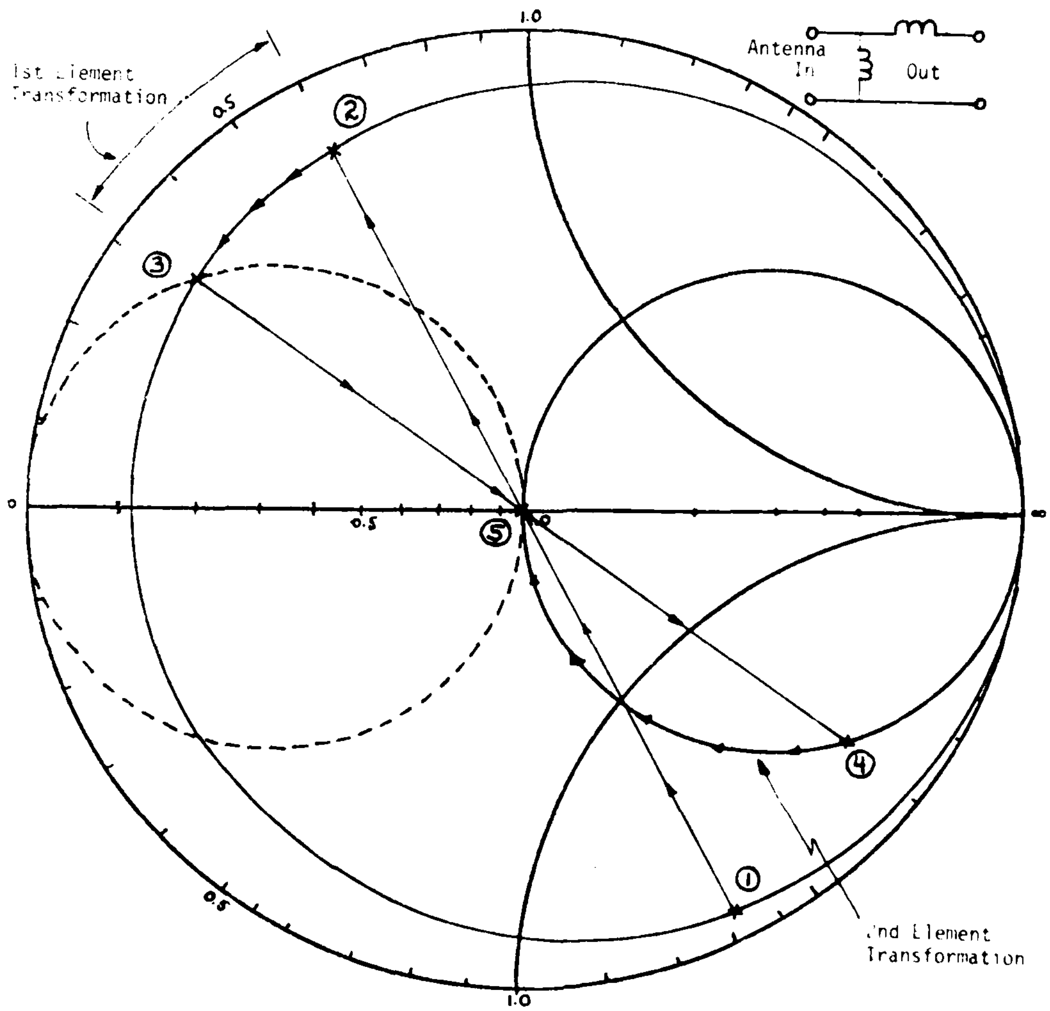


A.1. Type A (series input) L-network transformation.

We will assume that we want to match a small stub antenna using an L-network, and that the impedance of the antenna at some given frequency is at point 1 Fig. A-1. (It should be remembered that by simply reflecting all the points of interest in our discussion through the real axis on the Smith chart, the transformations to be shown will apply to the L-network required to match

the loop antenna). Note also in Fig. A-1, that both the real-part circle R=1 and its inverse (dashed circle) are shown. We use a series input L-network, and choose the first element immitance to provide a transformation of impedance (1) to impedance (2), i.e., to intercept the inverse R=1 (dashed) circle. All these transformations occur on constant R lines, since the network elements are assumed to be lossless. The next step is to invert from point (2) to point (3) on the R=1 circle. The immitance of the second element is then chosen to bring impedance (3) to the center of the chart, i.e., a perfect match. In general, if the values of the series and parallel elements are adjusted at each frequency of interest, a perfect match can be achieved. (Of course, as has been shown in the main body of this report, such matching cannot be achieved over a very broad band on an instantaneous basis).

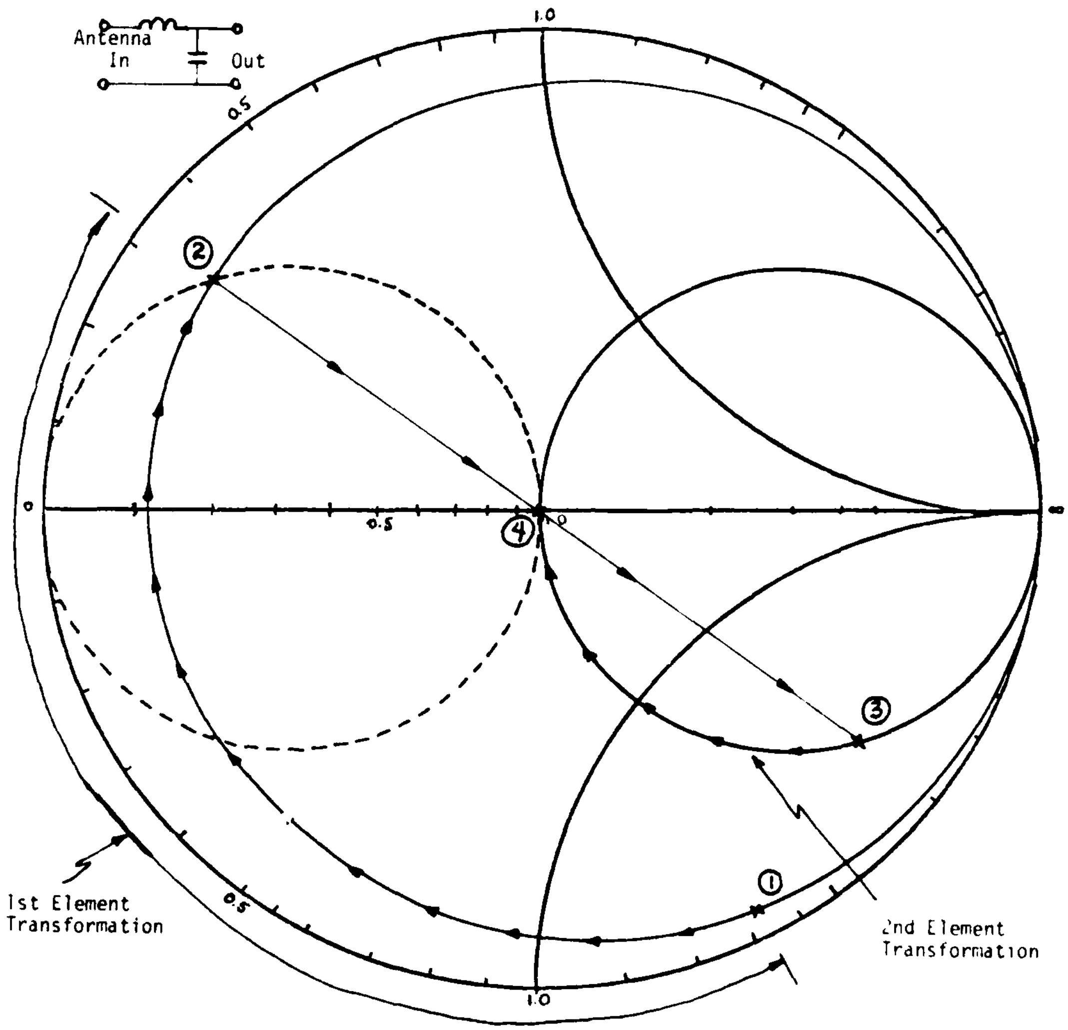
The transformation brought about by the parallel input L-network is shown in Fig. A-2. We start with the same impedance (1), but now the first



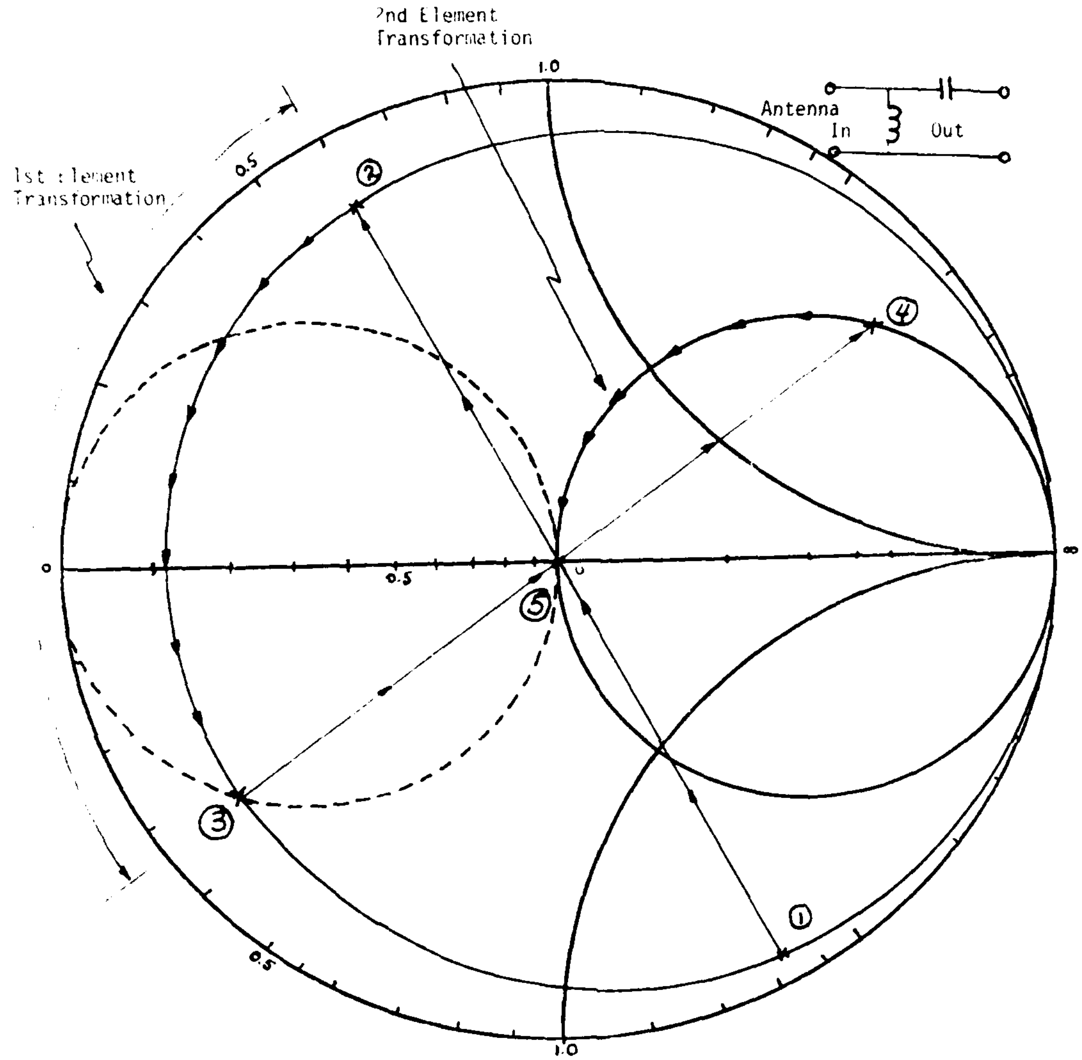
A.2. Type B (parallel input) L-network transformation.

step is an inversion to point (2). Then the shunt element immitance is chosen to cause a shift to point (3) on the inverse R=1 circle. A second inversion brings us to point (4) on the R=1 circle; then the series element immitance is chosen to yield a perfect match, point (5).

The first transformation in the examples shown in Figs. A-1 and A-2 could have been extended somewhat further by increasing the immitance of the first element to intercept the inverse R=1 circle at a point conjugate to the first intercept. This transformation is shown in Figs. A-3 and A-4 for both series- and parallel input L-networks, respectively. The result of this operation



A.3. Type A' (series input) L-network transformation.



A.4. Type B' (parallel input) L-network transformation.

is a change in the sign (and thus in the element type) of the immitance required for the second element. The complete transformation paths are shown in Figs. A-3 and A-4.

The four L-network configurations just discussed and the equivalent four networks used when considering a loop, represent all possible permutations. If the complex impedance versus frequency curve for an antenna is known the preceding tuning and matching procedure could be used to find the required immitance variations of the two elements in the L network over the entire frequency range. This, in fact, was done to generate the curves presented in the main report. In this way, a good estimate of the maximum bandwidth achievable at the highest efficiency is obtained.

We will derive two simple expressions which give all of the necessary information. Assume an immitance I, s.t.

$$I = RP + jIP \tag{A-1}$$

where RP is the real part, and IP is the imaginary part of I. Recall from the transformations depicted in Figs. A-1 and A-2 or figs. A-3 and A-4 that the first step in the transformation consists of several parts, i.e., either a shift to the inverse R=1 circle; or an inversion, followed by a shift to the inverse R=1 circle.

The final step, i.e., inversion to the R=1 circle, provides the equation for calculation of the required immitance variation of the first element. For lossless elements, the first transformation occurs along a constant resistance circle R=RP'. The new immitance, I', is given by:

$$I' = RP' + jIP', \tag{A-2}$$

where in the case of the series input network, RP'=RP in Eq. (A1); or when using the parallel input network $RP' = RP/(RP^2+IP^2)$. IP' is the new imaginary part. Inverting, we obtain

$$\frac{1}{I'} = \frac{RP'}{(RP')^2 + (IP')^2} - j\frac{IP'}{(RP')^2 + (IP')^2}. \tag{A-3}$$

But upon inversion, the R=1 circle is intercepted; thus (A-4)

$$\frac{RP'}{(RP')^2 + (IP')^2} = 1$$

Solution of (A-4) for IP' yields

$$IP' = \sqrt{RP'(1-RP')}. \tag{A-5}$$

Thus the magnitude of the required immitance for the first part of the transformation is given by

$$|\Delta IP_1| = \left||IP_1| - |IP_1'|\right|, \tag{A-6}$$

where in the series input case, $IP_1 = IP$; or in the parallel input case, $IP_1 = IP/(RP^2+IP^2)$.

The magnitude of the required immitance variation for the second element is given by

$$\Delta IP_2 = \left| \frac{IP'}{(RP')^2 + (IP')^2} \right| , \tag{A-7}$$

or, using Eq. (A5), by

$$\Delta IP_2 = \sqrt{\frac{(1-RP')}{RP'}} \; . \tag{A-8}$$

We generalize the derivation to provide the immitance variations required to intercept any real-part circle by setting Eq. (A-4) equal to the desired real part, r, i.e.,

$$\frac{RP'}{(RP')^2 + (IP')^2} = r, \tag{A-9}$$

from which we find

$$IP' = \sqrt{\frac{RP'(1-r\ RP');}{r}} \tag{A-10}$$

and substituting Eq. (A10) into Eq. (A7), we have

$$\Delta IP_2 = \sqrt{\frac{r(1-rRP')}{RP'}} = \left(\frac{r}{RP'}\right) IP'. \tag{A-11}$$

Equations (A-6), (A-10), and (A-11) have been used to generate the curves presented in the main report. If the input variation-with-frequency of the antenna is known, the required L-network element variations can be found and compared to realizable lossless element variations in order to determine the bandwidth.